Relationships Among Elements of the Sediment Quality Triad in Puget Sound

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[**Editor's note.** Figures for Long et al are located at the end of this document.]

Abstract
Surficial sediments were collected at 300 locations during 1997-1999 from the U.S./Canada border to the inlets of southern Puget Sound and Hood Canal. Statistical and graphical analyses were performed to quantify and illustrate the relationships among measures of chemical contamination, acute toxicity in laboratory tests, and indices of benthic infauna community structure in the sediments. Correlation and principal components analyses indicated a recurring pattern: one or more of the four toxicity tests indicated increasing degrees of response as the concentrations of mixtures of organic substances and trace metals increased among sampling locations. Indices of contamination by complex chemical mixtures were very important variables Soundwide; however, there were important differences in the composition of the mixtures among four urban bays that were examined in detail. Gradients in chemical concentrations and the degree of response in toxicity tests were accompanied by losses in numbers and abundance of sensitive benthic species that lead to declines in total numbers of species and numbers of dominant species. The most important taxonomic groups and individual benthic species indicative of contaminated conditions differed among some of the urban bays. Losses in sensitive species overshadowed the increases in abundance of several pollution tolerant organisms. One or more physical factors (water depth, salinity, organic carbon content, or grain size) were invariably as important as the chemical variables and, therefore, probably contributed to the accumulation of the toxicants in the sediments and to characteristics of the benthic assemblage composition.

Introduction
Toxic substances introduced into estuarine ecosystems, such as Puget Sound, can bind to suspended particles, settle to the bottom, and become incorporated into deposited soft sediments (NRC, 1989). As a result, sediments are an important medium in which to record the degree and history of chemical contamination of estuaries and bays. A considerable amount of monitoring and research has been conducted on toxicants and their effects in the Puget Sound region, including measures of sediment quality (Long 1987). Invariably, chemical contamination and toxicant-induced effects to the benthos and demersal fishes were most severe in the industrialized harbors and urbanized bays of Puget Sound and least severe in the rural bays and open basins farthest from sources (Long 1987; Llanso et al. 1998a, b; Malins et al. 1988; Becker et al. 1987). However, the data from these studies often indicated that the nature of toxicant mixtures that were related biological effects were somewhat different among the bays and harbors.

The purpose of this paper is to quantify and illustrate the relationships among individual variables of the sediment quality triad (chemical contamination, toxicity, benthic impacts) in Puget Sound, using data from a large-scale survey conducted with internally consistent methods during 1997-1999. Specific objectives were to identify which variables contributed significantly to overall variance among stations in sediment quality, to determine if the most significant elements differed among regions of the study area, and to illustrate the degree of concordance (including correlation) among elements of the triad of measures.

During the period 1997-1999, a survey of sediment quality was conducted throughout much of the region by the State of Washington Department of Ecology (Ecology) and the National Oceanic and Atmospheric Administration (NOAA). In this survey, 300 surficial sediment samples were collected following a probabalistic, stratified-random sampling design (Long et al., in prep). The Sediment Quality Triad approach, first introduced in Puget Sound (Long and Chapman 1985), was used. Data analyses were performed with individual measures of chemical contamination relative to applicable guidelines and criteria, measures of toxicity responses relative to negative controls, and indices of benthic composition relative to reference area conditions.

Methods

Sediments were sampled in the northern part of the study area during June of 1997 (Long et al. 1999), the central area in June of 1998 (Long et al. 2000), and the southern part, Hood Canal, and Commencement Bay in June of 1999 (Long et al. 2002). The same sampling and analytical methods were used in all three years; thus, ensuring that the data were comparable. In all cases, methods were selected to comply with protocols previously used by both Ecology in the Puget Sound Ambient Monitoring Program (PSAMP) and by NOAA in the National Status and Trends (NS&T) Program. Standardized methods for sample collections, chemical analyses, and benthic analyses in Puget Sound were previously described in the Puget Sound Estuary Program (PSEP) protocols (PSEP 1996a). Methods for sampling design, toxicity tests, and data analyses were used in comparable surveys of sediment quality conducted elsewhere in the U.S. by NOAA (Long et al. 1996; Turgeon et al. 1998).

Study Design

The study area encompassed the majority of the Puget Sound system, extending from the U.S./Canada border to the southern-most bays and inlets, including Hood Canal, but excluding the San Juan Islands and the Strait of Juan de Fuca (Figure 1). A probabilistic, stratified-random sampling design was used as in other surveys conducted by NOAA (Long et al. 1996) and by the Environmental Monitoring and Assessment Program (EMAP; Paul et al. 1992; Hyland et al. 2000) in U.S. estuaries. Sediments were collected with a double $0.1m^2$ van-Veen grab (PSEP 1987, 1996a). Sufficient amounts of surficial material (upper 2-3 cm) were removed from multiple deployments of the grab at each station to form a composite sample that was homogenized for chemical analyses and four toxicity tests. Benthic infauna samples were collected from the entire content of a single deployment of the $0.1\ m^2$ sampler at each station and data reported for organisms retained on 1.0-mm sieves. Water depths, bottom water salinity, temperature, and dissolved oxygen concentrations were recorded at each station.

Chemical Analyses

Analyses were performed for at least 157 (up to 172) chemicals and physical parameters, including trace metals, polynuclear aromatic hydrocarbons (PAHs), pesticides, phenols, phthalate esters, butyl tins, polychlorinated biphenyls (PCBs), other organic toxicants, total organic carbon (TOC), and grain size. Analytical protocols were comparable to those used nationwide by NOAA (Lauenstein and Cantillo 1993) and in Puget Sound by Ecology (PSEP 1986,1996b, c). Analytical procedures provided performance (i.e., recovery efficiencies, detection limits) equivalent to those used by NOAA and described in the PSEP protocols. Trace metals analyses were performed with both a strong acid-aqua region digestion and a total hydrofluoric acid digestion to comply with previous analyses for PSAMP and NS&T Program, respectively. Determinations of metals concentrations for both sets of extracts were made by ICP, ICP-MS, or GFAA, depending upon the appropriateness of the technique for each trace metal. Mercury concentrations were determined with U.S. Environmental Protection Agency (EPA) Method 245.5 by cold vapor atomic absorption (PSEP 1996c). Butyl tins were analyzed by methods that consisted of solvent extraction of sediment, derivitization of the extract with the Grignard reagent hexylmagnesium bromide, cleanup with silica and alumina, and analysis by Atomic Emission Detector.

Analyses for semi-volatile compounds and PAHs followed methods of U.S. EPA Method 846 8270, as recommended in PSEP (1996c), using capillary column, GC/MS techniques. U. S. EPA Method 8081 for chlorinated pesticides and PCB was used for the analysis of these compounds, using GC methods with dual dissimilar column confirmation and electron capture detectors. The concentrations of 20 target PCB congeners were determined following procedures outlined by NOAA (Lauenstein and Cantillo 1993).

Toxicity Tests

Four toxicity tests were performed, following standardized procedures. Amphipod survival tests of solid phase sediments, using the species *Ampelisca abdita*, followed the procedures of the ASTM (1993). Amphipods were exposed to test and negative control sediments for 10 days with 5 replicates of 20 animals each under static conditions using filtered seawater. Pore water was extracted from sediments with a pressurized squeeze extraction device (Carr and Chapman 1995) for toxicity tests performed with the gametes of the Pacific purple urchin *Strongylocentrotus purpuratus*. The tests consisted of 30-min exposures to three pore water concentrations, following protocols of the U. S. Geological Survey (Carr and Chapman 1995; Carr et al. 1996a, b; Carr 1998). The percentages of fertilized eggs were counted upon termination of the tests.

Two tests were performed on organic solvent extracts of the sediments. Cytochrome P-450 assays of the light produced by luciferase in a human reporter gene system (HRGS) of cultured liver cells were conducted, following standard protocols (Anderson et al. 1995, 1996, 1999; APHA 1996; ASTM 1997). The degree of response in this test is related to the concentrations of mixed-function oxygenase inducing chemicals in the sample. Data were converted to µg of benzo[a]pyrene equivalents per gram (µgB[a]P/g) of sediment. In another portion of the extracts, microbial bioluminescence (Microtox[tm]) tests were performed with protocols initially developed for Puget Sound (PSEP 1995; Schiewe et al. 1985) in a series of four sample concentrations. The amount of light lost per sample was assumed to be proportional to the toxicity of that test sample (Johnson and Long 1998). The concentrations of the extract that inhibited luminescence by 50% after a 5-min exposure period, the EC50 value, were determined and expressed as mg equivalent sediment wet weight.

Benthic Analyses

All field sampling methods, analytical procedures, and documentation followed those described in the PSEP protocols (PSEP 1987). A single 0.1 m^2 benthic sample was collected at each station and the entire contents sieved with a 1.0 mm sieve in the field. Sorting of taxonomic groups, identification to species level (when possible), and enumeration of organisms followed standard protocols developed for Puget Sound (PSEP 1987). After staining with rose bengal all organisms were examined under dissection microscopes. Sorting QA/QC procedures consisted of resorting 20% of each sample by a second sorter to determine whether a sample sorting efficiency of 95% removal was met. If the 95% removal criterion was not met, the entire sample was resorted. Organisms were enumerated and identified to the lowest taxonomic level possible by regional specialists. When possible, at least two scientific references were used to verify the identity of each species. Taxonomic identification quality control for all taxonomists included re-identification of 5% of all samples identified by the primary taxonomist and verification of voucher specimens generated by another qualified taxonomist.

Data Analyses

Chemical concentrations were evaluated either on an absolute (dry wt.) basis or as mean Sediment Quality Guideline (SQG) quotients. The SQG quotients were calculated with the Sediment Quality Standards (SQS) specified in the Washington State Sediment Management Standards (Chapter 173-204, WAC) and with the Effects Range-Median (ERM) values developed for NOAA (Long et al. 1995; 1998). Mean SQS quotients for 45 substances and mean ERM quotients for 25 substances were calculated as indices of contamination by chemical mixtures. Results of amphipod survival and urchin fertilization were treated as percentages of controls. Microtox test results were treated as EC50's. HRGS assay results were treated as benzo[a]pyrene equivalents.

No multi-metric benthic infaunal indices equivalent to those developed elsewhere (e.g., Van Dolah et al. 1999) are available thus far for Puget Sound. Therefore, nine benthic indices commonly used in Puget Sound were calculated to summarize the raw data. They included total abundance (total identifiable infaunal animals present), total numbers of taxa present, Pielou's evenness (J'), Swartz's dominance index (SDI, the numbers of species present that represented 75% of the total abundance), and the abundance of five taxonomic groups (annelids, arthropods, molluscs, echinoderms, other). In addition, the relative abundance of selected indicator species was included.

Spearman-rank correlation analyses were conducted using Abacus Statview software to identify and quantify the relative degree of correspondence between independent and dependent variables. Correlation coefficients for chemical, toxicity, and benthic variables were calculated with data from all 300 samples. Significance (p) values of <0.001 or <0.0001 were regarded as highly significant and would remain so if the number of variables and samples were taken into account. Selected relationships were shown graphically in bivariate scatterplots.

Principal components analyses (PCA) were conducted on the data to identify the most important variables in overall sediment quality and to illustrate spatial clusters among samples based on the important variables. Five trials of PCA were performed; one each with subsets of data from four urban bays (Everett Harbor/Port Gardner, Sinclair Inlet/Rich Passage, lower Duwamish River/Elliott Bay, and Tacoma waterways/Commencement Bay) and using all data combined from the four regions (n=80). Data from the four urban bays were selected to represent the greatest ranges in sediment quality among contiguous sampling strata. The PCAs were performed with 45 variables: 12 chemical, 4 physical, 3 toxicological, and 26 benthic community variables (Table 1). The correlation matrix instead of the covariance matrix was used to standardize differing scales among the variables. Prior to performing the PCA, the distribution of each of the individual variables was evaluated using histograms. Many variables showed moderate or high levels of skewness. Skewness was improved by either applying natural-log or square-root transformations to the data (see Table 1).

Results

Correlation Analyses
A summary of the highly significant correlations between independent and dependent variables in the entire database (n=300) indicated a significant degree of co-variance among many of the individual parameters included in the triad of analyses (Table 2). Many of the chemical concentrations increased with increasing organic carbon content and percent fine-grained materials along with decreasing bottom water salinity and depths. That is, the concentrations of chemicals tended to increase in the shallower (often dredged) reaches of the urban bays and harbors, especially in the mouths of industrialized rivers, that were nearest the sources of fine-grained particles and organic matter. Calculated indices of benthic diversity (i.e., H' diversity, numbers of species, SDI) decreased with increasing concentrations of organic matter and fine-grained particles. That is, some species that were abundant in deeper stations with lower organic carbon content and percent fines did not occur in organically enriched, fine-grained sediments. The relative abundance of echinoderms decreased as salinity decreased; thereby indicating decreased abundance in the mouths of rivers such as the Duwamish and Snohomish.

The 25 chemical concentrations accounted for with ERM values and the 45 chemicals accounted for with SQS values co-varied with each other, but the correlation (rho = 0.210, $p<0.001$) was not as significant as expected. Therefore, it appears that the 45 substances (including phthalates, phenols, benzoic acid) taken into account with the SQS values were distributed somewhat differently than the 25 chemicals accounted for with ERM values.

More toxicological and benthic variables were highly correlated with the two chemical indices than with any other variables. Co-varying significantly with the two increasing indices of chemical contamination were increasing levels of response in two or three of the toxicity tests and multiple indices of benthic diversity. Percent urchin egg fertilization decreased and the HRGS response increased significantly in association with increases in both chemical indices. The association between the magnitude of response in the HRGS assays and the concentrations of summed PAHs was especially strong. Swartz's dominance index declined significantly with increasing concentrations of trace metals. The abundance of echinoderms, arthropods and to a lesser extent, molluscs, decreased with increasing TOC/percent fines, increasing contamination, increasing toxicity, and decreasing benthic diversity. The decline in abundance of the echinoderms was highly significantly related to increasing responses in both the HRGS and urchin fertilization tests. Four benthic indices of relative species diversity increased as Microtox EC50's increased (i.e., indicative to declining degree of response). Overall, it appeared that both the concentrations of toxicants and natural variables were important variables for indices of diversity and relative abundance of several taxonomic groups. The abundance of annelids increased along gradients in contamination as indicated with the mean SQS quotients, probably attracted to the organic matter that tended to accumulate the toxicants.

Four of the most significant relationships identified in these analyses were selected to illustrate graphically (Figures 2 – 5). The scatterplots were prepared to better understand nature of the relationships ostensibly indicated with the correlation coefficients.

The strong correlation (Spearman's rank rho = 0.818, $p<0.0001$) between the response in the HRGS assay and the summed concentrations of 13 PAHs is illustrated in Figure 2. The graph shows that the majority of samples from Puget Sound had very low concentrations of PAHs (mean ERM quotients for PAHs <0.2). In concordance with these low concentrations, the responses in the HRGS assay were very low (<100 ug b[a]p equivalents/g). Cytochrome p-450 induction increased in many samples as PAH:ERM quotients increased above 0.2; however, this was not a steep linear relationship. Three samples (numbers 294-296) from the Thea Foss waterway near Tacoma had the highest responses in this assay (356, 529, 1995 ug/g). The outcome for the sample from station 294 is shown outside the scale of the graph (mean ERM quotient of 3.96, HRGS response of 1995 ug/g). It appears as though these three samples may have had a disproportionately high influence on the correlation. However, by omitting the data from these three samples, the correlation coefficient decreased only to 0.814 from 0.818. Thus, it appears that the high correlation was influenced mainly by samples with quotients in the 0-0.5 range, less so by the more contaminated samples.

A strong association also was apparent between mean SQS quotients for 8 metals and the SDI in the 300 samples (rho = -0.425, $p<0.0001$). The bivariate plot of these data showed a wide scatter in SDI values in the samples with lowest metals concentrations (quotients <0.1) (Figure 3). The numbers of dominant species ranged up to 44 and often exceeded 20 in the least contaminated samples. SDI values generally decreased below 15 and 10 species as the mean quotients for metals increased above 0.1 and 0.2. Fourteen samples with metals quotients of about 0.4 or greater were collected in the Tacoma waterways, Elliott Bay, inner Everett Harbor, and inner Sinclair Inlet. With one exception, SDI values in these samples were relatively low, ranging from 2 to 12. Sediment from station number 94 in Everett Harbor had a trace metals quotient of 1.0 (the highest observed) and 16 dominant species.

The relationship between the response in the HRGS assay and the relative abundance of the benthic echinoderms is illustrated in Figure 4. There is no known mechanistic linkage between cytochrome P-450 induction as determined in the HRGS assay and the abundance of echinoderms in the benthos. Therefore, this association is viewed as indicative of the relationship between a biochemical indicator of chemical contamination and an indicator of overall benthic community condition. The graph shows a wide scatter in echinoderm abundance among many stations in which P-450 induction was lowest (<20 ug/g). Some of these samples had as many as 600 echinoderms. The abundance of these organisms declined to 0 – 50 individuals as P-450 induction increased above 20 ug/g. There were 0, 41, and 38 echinoderms, respectively, in the samples from stations 294, 295, and 296 in the Thea Foss waterway near Tacoma in which the HRGS assay responses were highest.

Percent urchin fertilization in the porewater tests was significantly correlated with the abundance of both the arthropods (rho = .294, p<0.0001) and echinoderms (rho = 0.220, p<0.001) in the benthos (Table 2). The abundance of echinoderms was consistently low and ranged from 0 to 66 (average: 3.1, median: 0) in 63 samples in which control-normalized fertilization success was 0 – 96% (Figure 5). In contrast, the abundance of these organisms increased remarkably (ranging from 0 to 650, average: 34.9, median: 1) in 237 samples in which fertilization success was 97% of controls or greater. The graph indicates that there were many samples with low echinoderm abundance when fertilization success exceeded about 97% or greater, but, more importantly there were no samples with high echinoderm abundance when fertilization success was lower.

Principal Components Analysis

The first trial of the PCA was performed with data from 45 variables measured in 80 samples selected to represent the expected pollution gradients in the four urban bays combined together (Table 3). Only 22% of total variance was explained in the first principal component, 45% in the first three components, and 65% in all six components. In the first component, the strongest correlations (>0.500) were apparent for 16 variables, including six chemical classes or mixtures, three toxicity tests, six benthic indicators, and two physical variables. The data indicated that the concentrations of phenols, eight metals analyzed with partial digestions, nine metals analyzed with total digestions, the mean ERM quotients and the mean SQS quotients increased with decreasing depth and increasing TOC content. HRGS induction increased, Microtox EC50's decreased, and urchin fertilization success decreased; therefore, indicating that the degree of responses in the three tests increased as chemical concentrations increased. The numbers of total taxa, the numbers of dominant taxa, and the abundance of molluscs, phoxocephalid amphipods, and other taxa decreased as chemical concentrations increased. Conversely, the abundance of capitellids increased along these gradients. Thus, there were losses in benthic diversity, losses in sensitive taxa, and increases in pollution-tolerant taxa as chemical contamination and measures of toxicity increased. The most important variables (correlations > 0.700) were mean ERM quotients, TOC content, concentrations of phenols, and the abundance of capitellids.

In the second component for the combined four urban bays, the important variables consisted of the concentrations of PCB aroclors, and low- and high–molecular weight PAHs increasing as depth and percent fines decreased (Table 3). Total abundance and total numbers of taxa in the benthos increased along with the abundance of two indicator species: *Aphelochaeta* and *Parvilucina*. In the third component, the index of benthic evenness increased, abundance of arthropods increased and abundance of *Axinopsida* decreased as percent fines and urchin fertilization success decreased, but none of the chemical variables were important.

The bivariate plot of the first and second principal components calculated with the data from 80 stations shows a number of clusters of stations, some well-defined along the axes of the first or second components or both, and others poorly defined and overlapping with other clusters (Figure 6). At the far right side of the diagram, the four inner Everett Harbor stations appear as having the poorest sediment quality along the axes of both components. That is, they had, overall, the highest concentrations of toxic chemicals, the highest responses in the toxicity tests, and several indicators of low benthic species diversity. They also had relatively high TOC concentrations and low water depths. Relatively high total benthic abundance was a consequence of the presence of prolific assemblages of pollution-tolerant species. The gradient of improving conditions (towards the left of the diagram) is apparent along the axis of the first component (but, not the second component) into middle and outer Everett Harbor and, again, into Port Gardner Bay (i.e. seaward of the harbor).

Four stations from inner Sinclair Inlet were similar to the Everett mid-and outer harbor stations (Figure 6). Conditions at the lower Duwamish River/inner Elliott Bay stations were similar to those in the waterways of Commencement Bay and fell into the upper right quadrant. That is, they were clustered together as a result of having similar concentrations of PCB aroclors, PAHs, and total abundance of benthos, including the presence of pollution-tolerant species. Conditions within the four Commencement Bay waterways (Hylebos, Blair, Middle, Thea Foss) were sufficiently different to be identifiable in the diagram. Stations from outer Commencement Bay, Outer Elliott Bay, Port Gardner Bay, and the Central Basin were among the least degraded along the first principal component, but separated along the axis of the second component. The stations in Rich Passage were mixed with many stations from mid-and outer Elliott Bay in the upper left quadrant of the diagram and thus were indicated as the least degraded.

A comparison of the results in all five PCA trials strongly indicates that the chemical nature of the contamination differed from place to place in the four urban bays of Puget Sound (Table 4). One or both of the indices of chemical contamination by mixtures were very important variables in all four urban bays individually or combined. Whereas benzoic acid, PCBs, PAHs, and phthalates were not important variables in the four bays combined, benzoic acid was important in Everett Harbor and Sinclair Inlet, and PCBs were important in Sinclair Inlet, Elliott Bay, and Commencement Bay (but not in Everett Harbor). Both the LPAHs and HPAHs were important in Everett Harbor and Commencement Bay. However, only the LPAHs were important in Sinclair Inlet, whereas only the HPAHs were important in Elliott Bay. Phthalates were important positive contributors to variance in only Commencement Bay, whereas they were a negative variable in Sinclair Inlet. Trace metals, as determined with either digestion method, were not important in Everett Harbor and Elliott Bay, whereas they were highly important in the four bays combined and in Sinclair Inlet and Commencement Bay. In contrast to the bay-specific distributions of the chemical groups mentioned above, the concentrations of phenols were consistently important variables in all four bays. In addition, the two indices of multiple chemical mixtures (mean ERM quotients for 25 substances and mean SQS quotients for 45 substances) were highly important in the four bays combined and in three of the individual bays. Only the mean ERM quotients were important in Sinclair Inlet where the addition of the SQS-specific substances to the index appeared to have significantly altered the nature of the index values.

As observed for the chemical variables, the relative importance of the physical variables that were measured differed among the four urban bays (Table 4). The depths of the sampling locations and TOC concentrations were important Sound-wide, and in Everett Harbor and Commencement Bay. Grain size and TOC were important in Sinclair Inlet where salinity was not important because of the lack of a riverine tributary. The Duwamish River enters Elliott Bay and was included in the sampling design. The Puyallup River enters Commencement Bay, but was not sampled. The Snohomish River enters Port Gardner Bay near Everett, but was not sampled. Accordingly, salinity was an important variable (along with depth) in Elliott Bay, whereas it was not important in either Everett Harbor or Commencement Bay.

A recurring pattern among these data was one in which one or more of the toxicity tests (always HRGS, often urchin fertilization and/or Microtox) indicated increasing toxicity as the concentrations of mixtures of toxicants increased among sampling locations. Results of the HRGS assays were important variables in the first principal component in the four bays combined and in each of them separately (Table 4). The Microtox and sea urchin tests also were important in the four bays combined and in two or three of them separately, but not in the same bays.

Increases in chemical concentrations and toxicity were usually accompanied by losses in abundance of sensitive benthic species that lead, in turn, to declines in total numbers of species and numbers of dominants. Among the calculated benthic indices, the numbers of taxa and the index of dominance were consistently important in the four bays combined and in Everett Harbor and Sinclair Inlet, but only dominance was important in Elliott Bay and none of the calculated indices was important in Commencement Bay (Table 4). Total organism abundance was important in Everett Harbor and Elliott Bay, whereas Pielou's evenness was important only in Sinclair Inlet and Elliott Bay.

The phyla that were important variables included the molluscs and "other" taxa in the four bays combined and in Everett Harbor and Sinclair Inlet, but only the taxa categorized as "other" were important in Elliott Bay and neither was important in Commencement Bay. Neither the arthropods nor the echinoderms were important variables in the four bays combined and they were important in only one or two of the individual bays. This outcome was not expected, given the fidelity of both taxonomic groups with ranges in mean SQG quotients as shown in the correlation analyses for the entire data set. The individual taxa that were important contributors to total variance differed among regions and only the capitellids and phoxocephalid amphipods loaded onto the first principal component in the four bays combined. In several regions, *Aphelochaeta* and/or the capitellids increased in abundance as contamination and toxicity increased and generally were inversely related in abundance to the phoxocephalids. A variety of different species, most often including the phoxocephalids and other amphipods, declined in abundance as taxa richness and dominance decreased and as chemical concentrations and toxicity increased. One or more physical factors (water depth, salinity, TOC content, or grain size) were invariably as important as the chemical variables and, therefore, probably contributed to the accumulation of the toxicants in the sediments and to the between-station differences in composition of the benthos.

Conclusions

Together, the battery of physical/chemical, toxicological, and benthic measures effectively identified gradients in relative sediment quality in each of the four urban bays and separated both the bays from each other and regions within each bay from each other in the PCA. There were remarkable differences in sediment quality among stations in each of the four urban bays, invariably indicated by decreases in quality near or within the industrialized harbors. Sediments from inner Everett Harbor had the poorest quality. Those from the Thea Foss and Middle waterways, lower Duwamish River, off the Seattle waterfront, and inner Sinclair Inlet also were among the most degraded.

These data analyses demonstrated that despite the observations that some variables were consistently important in all bays, there were many indications that the characteristics of the sediments that were important determinants of overall sediment quality also were either site-specific or bay-specific. The characteristics of the chemical mixtures in each urban bay overlapped or were similar to some degree. That is, the mean SQG quotients for 25 or 45 substances were important Sound-wide in the correlation analyses and in all four urban bays in the PCA. Therefore, many of the same substances were relatively ubiquitous. The PAHs were important independent variables for the HRGS assay and the trace metals were important for the urchin fertilization test. The phenols were important in all four urban bays. The abundance of benthic echinoderms throughout the Sound varied significantly with the levels of chemical contamination and toxicity and, also, with the geochemical factors (i.e., grain size, TOC) that were important determinants throughout the region in the accumulation of toxicants.

However, there were significant differences in the nature of the chemical mixtures and in the other measured variables among the bays. These differences were identified as the most important variables in the PCA trials. For example, PCBs were important in some areas, not in others. The trace metals were more important in two bays and not in the others. Porewater ammonia, PCBs, and benzoic acid were important in two or three bays, but not in the other(s). The LPAHs were more important than the HPAHs in one bay and vice versa in another bay. Depth and TOC content appeared to be important determinants of toxicant accumulation and benthic community composition throughout the Sound and in most bays, but not in all of them. The HRGS assay was consistently important Sound-wide and the HRGS, Microtox, and urchin tests often complimented each other. However, the nature and degree of the responses in the toxicity tests differed among bays. Throughout much of the Sound, there was a recurring pattern of decreasing diversity index values, numbers of taxa and dominant species associated with increasing levels of chemical contamination and responses in toxicity tests. These changes in the benthos often were a function of declining numbers and abundance of sensitive taxa and the proliferation of pollution-tolerant species. However, there were differences throughout the Sound and among the four urban bays in the composition of the benthos and in the calculated indices that were important. Thus, the characteristics of the benthic communities and their responses to stresses were in part bay-specific. Consequently, the specific response of the benthos to stresses in one area could not be predicted with data from another area.

The results of this study have important implications in the design of future monitoring programs that involve contaminated sediments. While sediment quality assessment tools (i.e., chemical guidelines, chemical indices, toxicity tests, benthic metrics) can and must be applied throughout the region to ensure consistency, it is readily apparent that the importance of these various tools differs from place to place. It can be anticipated that some chemicals that are highly important in one bay may not be important variables in another bay. Therefore, the set of sediment quality guidelines or criteria that are most helpful in determining overall quality may differ from place to place. Accordingly, the magnitude of response in toxicity tests can be expected to differ according to the makeup of the chemical mixtures, which can, in turn, differ among the urban bays. The benthic data indicated a few consistent patterns in response (i.e., losses of sensitive species, lower diversity indices) to gradients in contamination and toxicity, but the key indicator species can be expected to differ considerably in importance throughout the Sound. These parameters appear to differ in importance as a function of both anthropogenic and natural factors and probably it is impossible to distinguish between the two as causative factors.

Based on these data, it is apparent that a Sound-wide monitoring of sediment quality must continue to include a broad suite of physical/chemical, toxicity, and benthic analyses to ensure that internally consistent and comprehensive evaluations of sediment quality are conducted. Also, it is apparent that a narrow, more specific battery of analyses could be tailored for application to an individual urban bay to ensure cost effectiveness, but such limited analyses may not be as applicable and representative of overall environmental quality in another bay or region.

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Figures

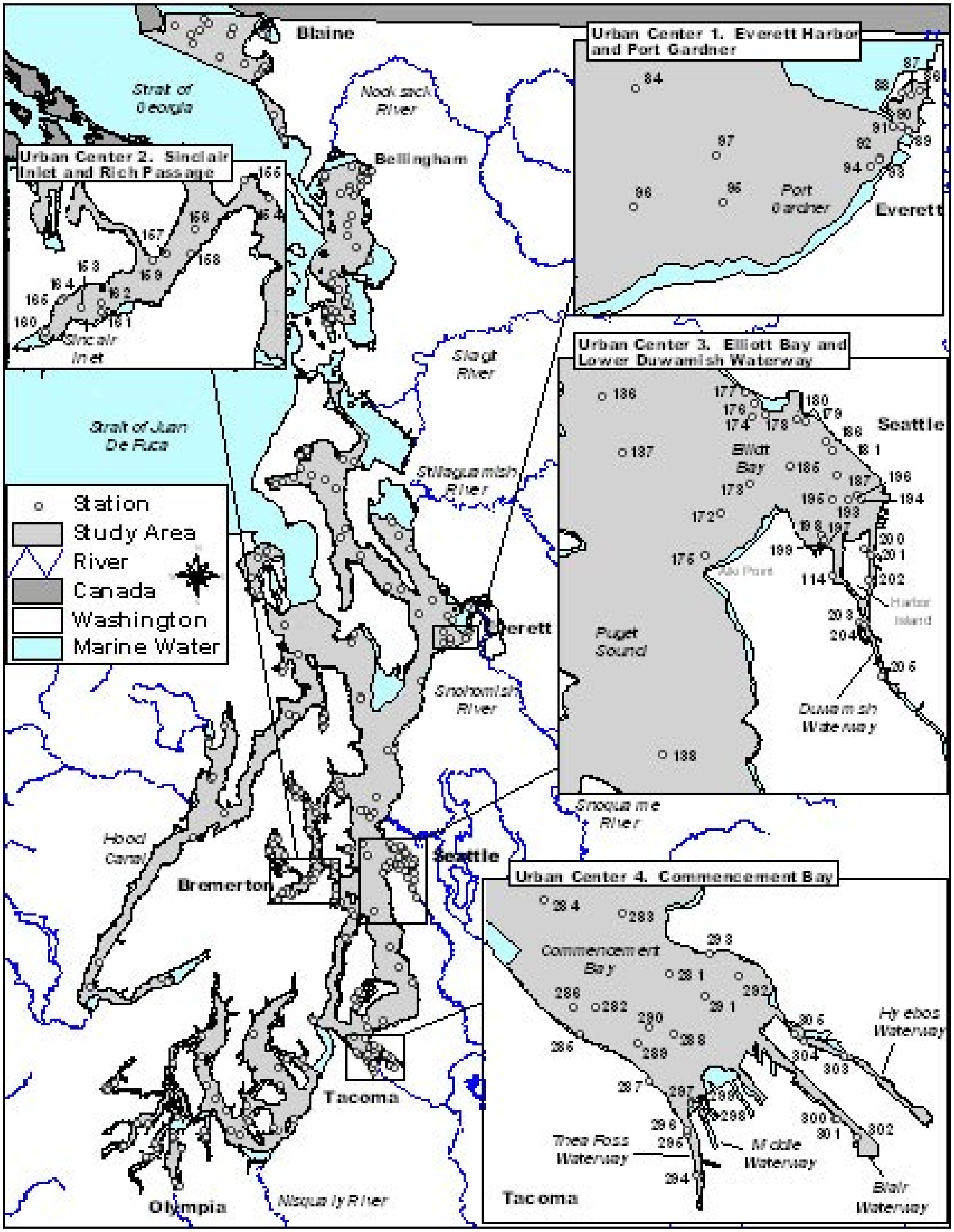

Figure 1. Locations of 300 sediment sampling stations in joint Ecology/NOAA survey of sediment quality in Puget Sound.

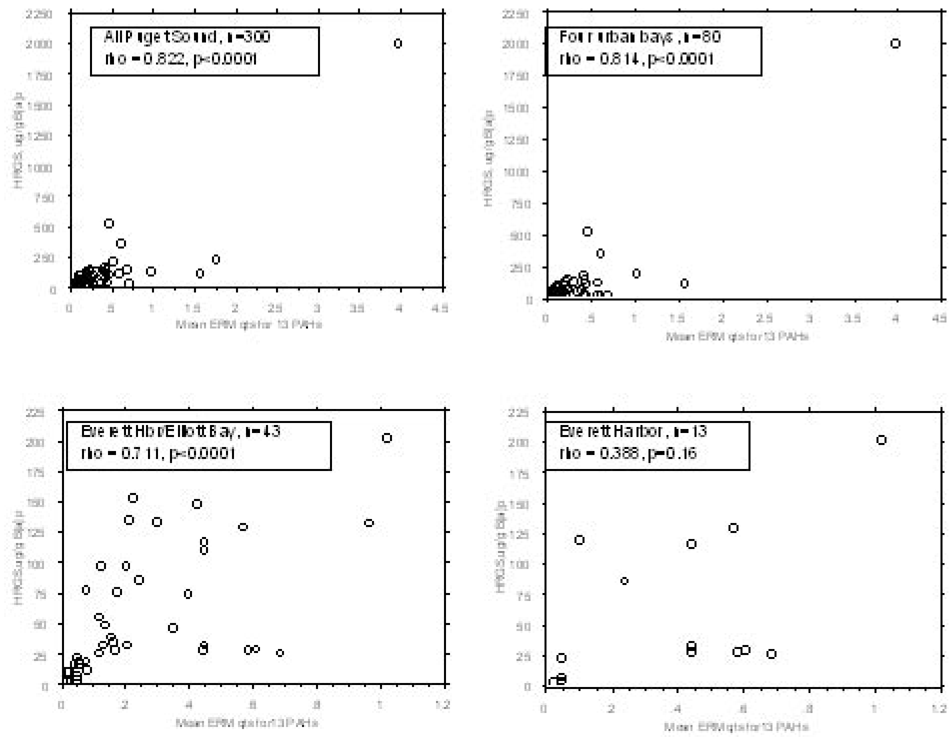

Figure 2. Relationships between HRGS assay responses (ug/g benzo[a]pyrene equivalents) and summed concentrations of 13 polynuclear aromatic hydrocarbons (mean ERM quotients for 13 PAHs) in sediments from Puget Sound (n=300), four urban bays (n=80), Everett Harbor/Elliott Bay (n=43), and Everett Harbor (n=13).

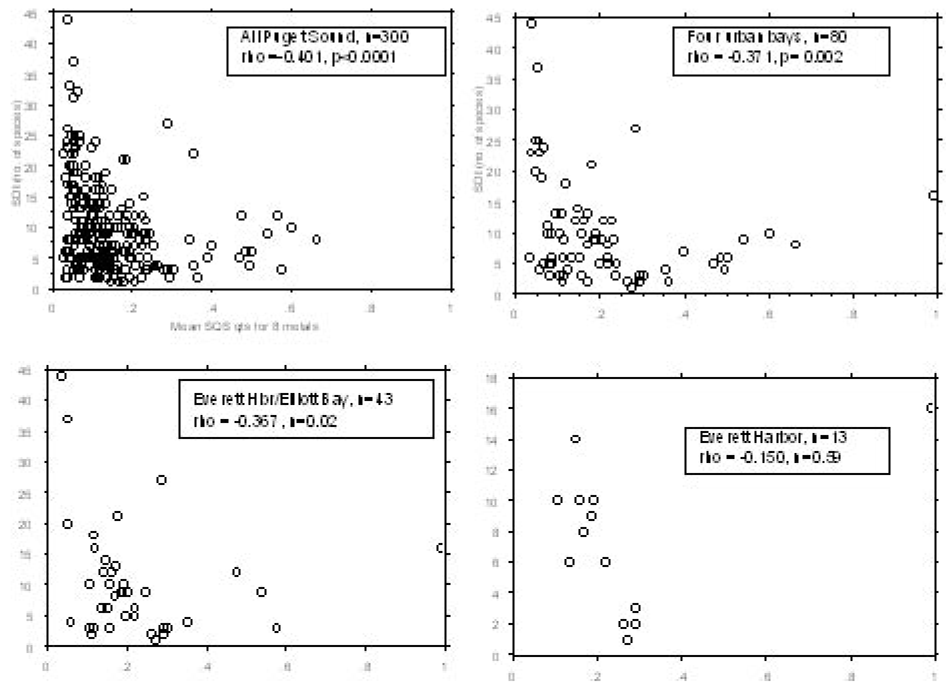

Figure 3. Relationships between Swartz's Dominance Index (SDI) values and mean SQS quotients for 8 trace metals in sediments from Puget Sound (n=300), four urban bays (n=80), Everett Harbor/Elliott Bay (n=43), and Everett Harbor (n=13).

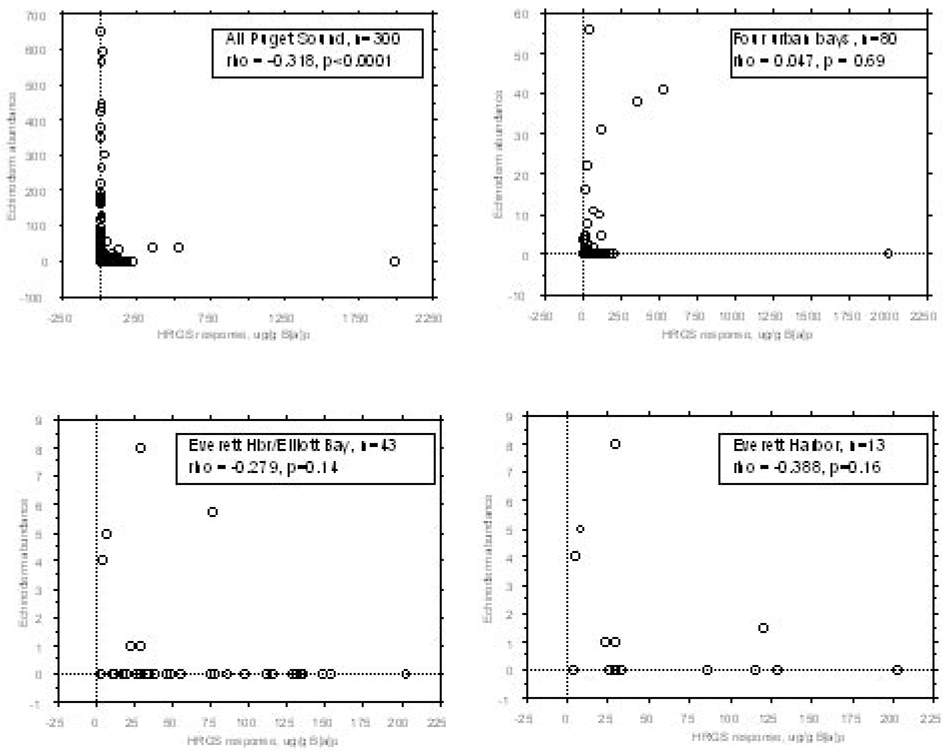

Figure 4. Relationships between the abundance of benthic echinoderms and the HRGS assays responses (ug/g benzo[a]pyrene equivalents) in sediments from Puget Sound (n=300), four urban bays (n=80), Everett Harbor/Elliott Bay (n=43), and Everett Harbor (n=13).

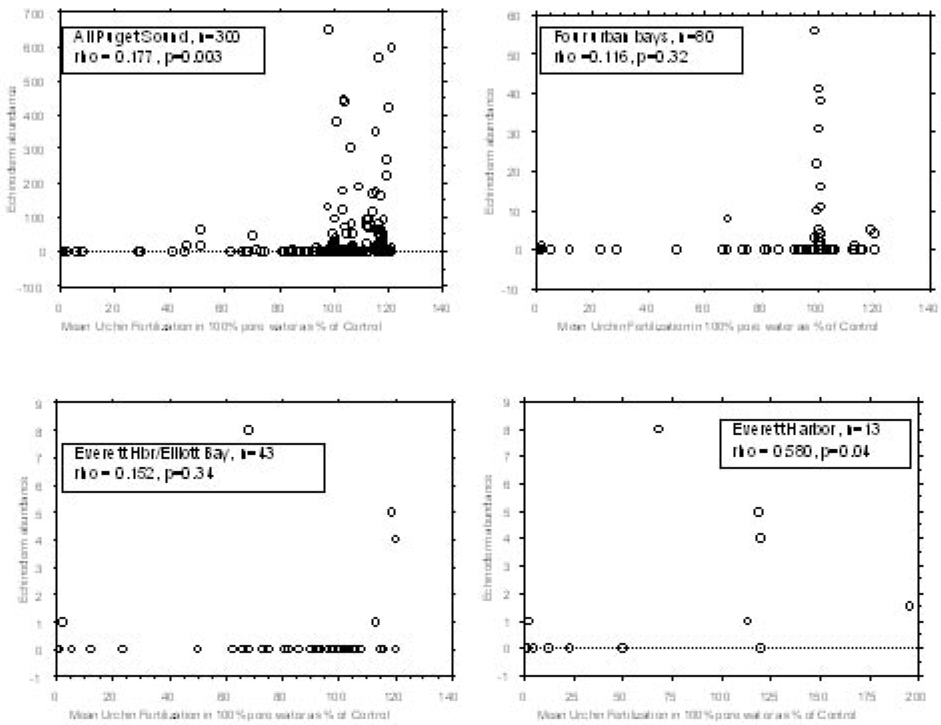

Figure 5. Relationships between the abundance of benthic echinoderms and percent sea urchin fertilization success (as percent of control response) in sediments from Puget Sound (n=300), four urban bays (n=80), Everett Harbor/Elliott Bay (n=43), and Everett Harbor (n=13).

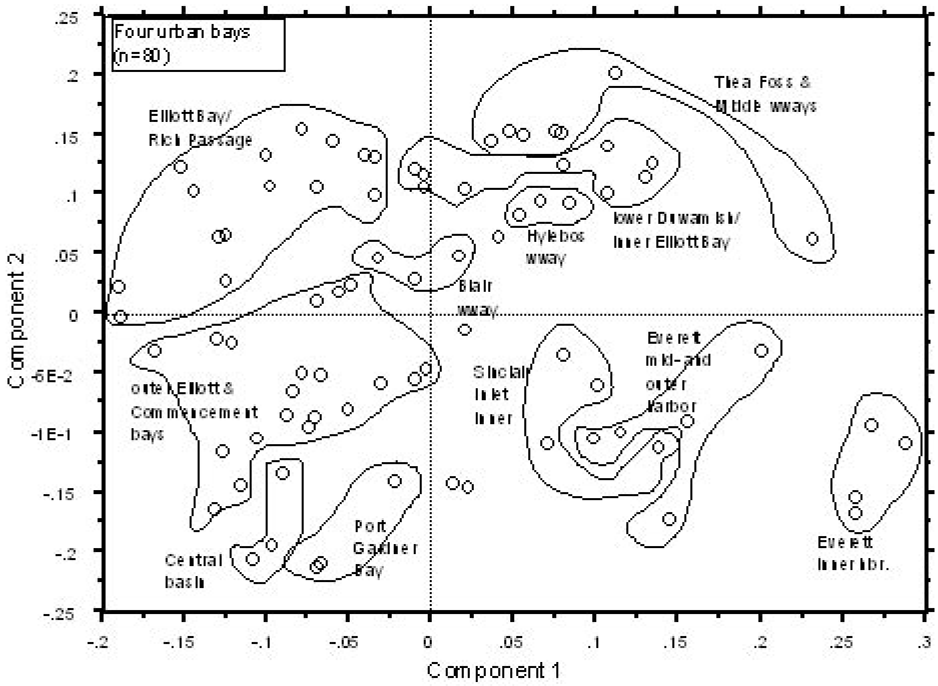

Figure 6. Relationships among sampling stations and clusters of similar stations based upon first and second principal components calculated for 80 selected stations selected from four urban bays in Puget Sound.